AFRL-RQ-WP-TP-2015-0150

HIFiRE-1 TURBULENT SHOCK BOUNDARY LAYER INTERACTION – FLIGHT DATA AND COMPUTATIONS (POSTPRINT)

Roger L. Kimmel

Hypersonic Sciences Branch
High Speed Systems Division

Dinesh Prabhu

NASA Ames Research Center

JUNE 2015

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*//Signature//   //Signature//
ROGER L. KIMMEL   MICHAEL S. BROWN, Chief
Project Manager   Hypersonic Sciences Branch
Hypersonic Sciences Branch   High Speed Systems Division
High Speed Systems Division   Aerospace Systems Directorate

//Signature//
THOMAS A. JACKSON
Deputy for Science
High Speed Systems Division
Aerospace Systems Directorate

REPORT DOCUMENTATION PAGE

1. REPORT DATE *(DD-MM-YY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
June 2015	Conference Paper Postprint	22 June 2014 – 22 June 2015

4. TITLE AND SUBTITLE
HIFiRE-1 TURBULENT SHOCK BOUNDARY LAYER INTERACTION – FLIGHT DATA AND COMPUTATIONS (POSTPRINT)

5a. CONTRACT NUMBER
In-house

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
61102F

6. AUTHOR(S)
Roger L. Kimmel (AFRL/RQHF)
Dinesh Prabhu (NASA Ames Research Center)

5d. PROJECT NUMBER
3002

5e. TASK NUMBER
N/A

5f. WORK UNIT NUMBER
Q1FN

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Hypersonic Sciences Branch (AFRL/RQHF)
High Speed Systems Division
Air Force Research Laboratory, Aerospace Systems Directorate
Wright-Patterson Air Force Base, OH 45433-7541
Air Force Materiel Command, United States Air Force

NASA Ames Research Center
Moffett Field, CA 94035

8. PERFORMING ORGANIZATION REPORT NUMBER

AFRL-RQ-WP-TP-2015-0150

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory
Aerospace Systems Directorate
Wright-Patterson Air Force Base, OH 45433-7541
Air Force Materiel Command
United States Air Force

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
AFRL/RQHF

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-RQ-WP-TP-2015-0150

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES
PA Case Number: 88ABW-2015-2427; Clearance Date: 18 May 2015.

This conference paper was published in the proceedings of the 45th AIAA Fluid Dynamics Conference, held June 22 - 26, 2015 in Dallas, TX. The U.S. Government is joint author of the work and has the right to use, modify, reproduce, release, perform, display, or disclose the work.

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14. ABSTRACT
The Hypersonic International Flight Research Experimentation (HIFiRE) program is a hypersonic flight test program executed by the Air Force Research Laboratory (AFRL) and Australian Defence Science and Technology Organisation (DSTO). This flight contained a cylinder-flare induced shock boundary layer interaction (SBLI). Computations of the interaction were conducted for a number of times during the ascent. The DPLR code used for predictions was calibrated against ground test data prior to exercising the code at flight conditions. Generally, the computations predicted the upstream influence and interaction pressures very well. Plateau pressures on the cylinder were predicted well at all conditions. Although the experimental heat transfer showed a large amount of scatter, especially at low heating levels, the measured heat transfer agreed well with computations. The primary discrepancy between the experiment and computation occurred in the pressures measured on the flare during second stage burn. Measured pressures exhibited large overshoots late in the second stage burn, the mechanism of which is unknown. The good agreement between flight measurements and CFD helps validate the philosophy of calibrating CFD against ground test, prior to exercising it at flight conditions.

15. SUBJECT TERMS
boundary layer transition, hypersonic, ground test

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor)
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**	SAR	14	Roger L. Kimmel
Unclassified	Unclassified	Unclassified			19b. TELEPHONE NUMBER *(Include Area Code)* N/A

HIFiRE-1 Turbulent Shock Boundary Layer Interaction – Flight Data and Computations

Roger L. Kimmel[*]
Air Force Research Laboratory, 2130 8ᵗʰ St., WPAFB, OH 45433, USA

Dinesh Prabhu[†]
NASA Ames Research Center, Moffett Field, California 94035

The Hypersonic International Flight Research Experimentation (HIFiRE) program is a hypersonic flight test program executed by the Air Force Research Laboratory (AFRL) and Australian Defence Science and Technology Organisation (DSTO). This flight contained a cylinder-flare induced shock boundary layer interaction (SBLI). Computations of the interaction were conducted for a number of times during the ascent. The DPLR code used for predictions was calibrated against ground test data prior to exercising the code at flight conditions. Generally, the computations predicted the upstream influence and interaction pressures very well. Plateau pressures on the cylinder were predicted well at all conditions. Although the experimental heat transfer showed a large amount of scatter, especially at low heating levels, the measured heat transfer agreed well with computations. The primary discrepancy between the experiment and computation occurred in the pressures measured on the flare during second stage burn. Measured pressures exhibited large overshoots late in the second stage burn, the mechanism of which is unknown. The good agreement between flight measurements and CFD helps validate the philosophy of calibrating CFD against ground test, prior to exercising it at flight conditions.

I.   Introduction

The Hypersonic International Flight Research Experimentation (HIFiRE) program consists of extensive ground tests and computation focused on specific hypersonic flight technologies.[1,2] Its purpose is to develop and validate technologies critical to next generation hypersonic aerospace systems. Candidate technology areas include, but are not limited to, propulsion, propulsion-airframe integration, aerodynamics and aerothermodynamics, high temperature materials and structures, thermal management strategies, guidance, navigation, and control, sensors, and system components. Each technology program is designed to culminate in a flight test. The first science flight of the HIFiRE series, HIFiRE-1, launched 22 March 2010 at the Woomera Prohibited Area in South Australia at 0045 Universal Coordinated Time (UTC) (1045 local time).

The primary objective of HIFiRE-1 was to measure aerothermal phenomena in hypersonic flight. The primary experiment consisted of boundary-layer transition measurements on a 7-deg half angle cone with a 2.5 mm radius nose. The secondary aerothermal experiment was a shock-boundary-layer interaction created by a 33-deg-flare / cylinder configuration. HIFiRE-1 ground test and computation created an extensive knowledge base regarding transition and shock boundary-layer interaction (SBLI) on axisymmetric bodies. This research has been summarized in numerous prior publications.[3,4,5,6,7,8,9,10,11,12,13,14]

Preliminary results from the HIFiRE-1 aerothermal experiments have been previously published.[15] Ref. 15 presented preliminary results from both the BLT and SBLI experiments during ascent and descent. Although the vehicle was at a higher angle of attack than intended during descent, the payload instrumentation scheme permitted acquisition of interesting and useful high angle-of-attack (AoA) transition data. [16,17] Analysis of the high AoA reentry SBLI experiment is considerably more difficult, so the current paper focuses only on the ascent-phase SBLI. A prior publication expanded on the SBLI experiment focused on unsteady pressure measurements.[18] The current publication focuses on comparing computations of the SBLI to flight measurements for the ascent phase of flight.

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[*] Principal Aerospace Engineer, Associate Fellow AIAA.

[†] Senior Research Scientist, Entry Systems and Technology Division; currently ERC, Inc., Mail Stop 229-1. Associate Fellow AIAA.

HIFiRE-1 presents an unusual test case for CFD, since highly-detailed surface measurements were made on a relatively simple configuration. Although the flight conditions were relatively benign, with a maximum Mach number of seven during reentry, computation of the turbulent SBLI is not trivial. Although CFD codes can be calibrated against wind tunnel results prior to applying them to flight conditions, it is generally not possible to match flight conditions exactly in ground test. HIFiRE-1 showed significant variations in flight conditions and wall temperatures during ascent. Freestream unit Reynolds numbers ranged from 0 to 60×10^6 per meter during ascent, and ascent Mach number varied from subsonic to approximately 5.5. Flare temperatures ranged from approximately 300 K to a peak of 540 K during ascent, and at any time varied significantly through the interaction. Computation of the HIFiRE-1 ascent turbulent SBLI provides an interesting test of a computer code calibrated against a point condition in a wind tunnel.

II. Experiment and Flight Profile

The HIFiRE-1 vehicle has been described in several prior publications, most notably in Ref. 14. The overall payload dimensions and the different payload modules are shown in Fig. 1. The experiments were carried out on the forward sections of the payload including a cone, a cylinder, and a flare that transitioned to the diameter of the second stage motor (0.356 m). The nose tip consisted of an iridium-coated, titanium-zirconium-molybdenum (TZM) alloy. The surface finish of the nose tip after coating was measured to be 6-8 microinches (0.15-0.2 microns) RMS (root mean square). The aluminum cone shell was finished to a 0.8 micron R_a finish (R_a is the arithmetic average of roughnesses). The cone half angle of seven degrees was chosen to match configurations used in preceding ground tests and analytical/numerical work. The aft-portion of the cylinder and the flare consisted of AISI 1045 steel.

The payload contained duplicate instrumentation on rays 180° apart, permitting a cross-check between instrumentation on these two rays. One ray of instrumentation contained a diamond-shaped trip to produce a roughness-induced transition. The payload incorporated this feature to ensure that turbulent data might be obtained even if the reentry portion of the flight terminated before natural transition occurred. Pressures and temperatures on the flare on this ray were recorded throughout flight. The circuit board that conditioned SBLI pressures on the cylinder on this ray failed at approximately t=6 seconds, therefore no data were recorded from these instruments after this time.

The ray of instrumentation 180° opposite of the trip contained no intentional trip element. However, backward-facing steps on the nosetip of the vehicle tripped transition for t<11.5 seconds. For t>11.5 seconds, transition moved aft with time over the conical portion of the vehicle, until about t=21.5 seconds. At this point, flow over the cone was entirely laminar. The SBLI began to take on characteristics of a transitional interaction at about this time.
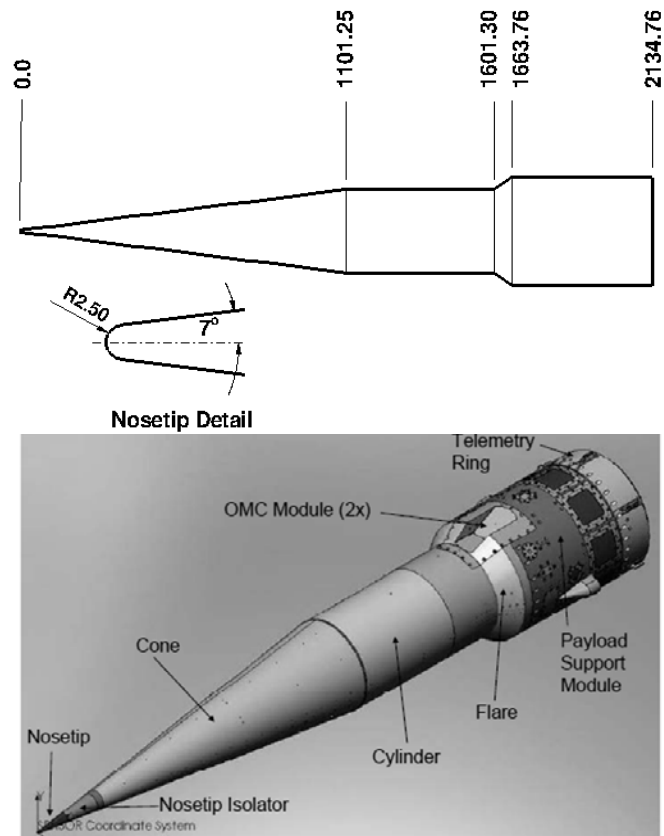
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Fig. 1 HIFiRE-1 payload configuration, dimensions in mm

The payload flew a ballistic trajectory similar to those employed for the HyShot[19] and Hypersonic Collaborative Australia/United States Experiment (HyCAUSE)[20] flights. The as-flown trajectory is shown in Fig. 2. The Terrier first stage burnt for 6.3 seconds and was then drag-separated from the second stage. The Orion/payload combination coasted until the second stage ignited at 15 seconds. Orion burnout occurred at 43 seconds. The payload remained attached to the second stage throughout the entire flight to provide stability as the payload reentered the atmosphere. Approximately the first and last 45 seconds of the trajectory were endoatmospheric. The remainder of the trajectory was exoatmospheric.
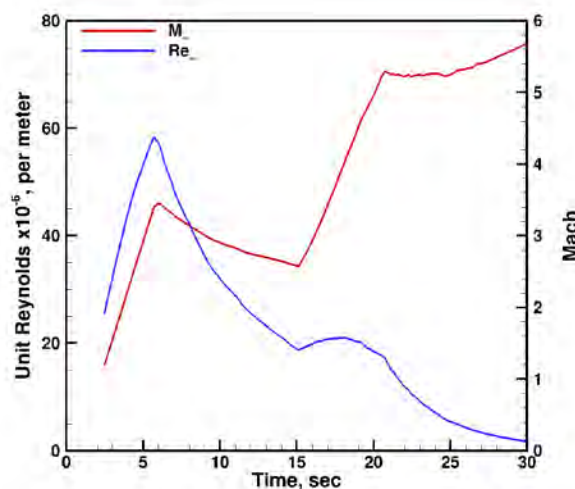
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Fig. 2 HIFiRE-1 as-flown trajectory

A prior publication described the HIFiRE-1 mission.[21] The most notable complications in the mission were failures of the on-board Global Positioning System (GPS) and the exoatmospheric pointing maneuver. The loss of the GPS meant that the vehicle altitude and velocity had to be reconstructed from existing data such as accelerometers, radar tracks, etc. References 15 and 21 describe development of the best estimated trajectory (BET). The failure of the exoatmospheric pointing maneuver was a more serious malfunction, since it caused the vehicle to enter the atmosphere with an angle of attack as high as 40-deg. Although angle-of-attack oscillations damped and decreased as the vehicle descended, the payload angle of attack was still over 10-deg as aerothermal data began to be collected during descent. Since the risk of this occurrence was recognized prior to flight, the payload flew unshrouded, i.e. no nosecone shell covered the experiment during ascent. This permitted low-angle-of-attack (< 1 deg) data to be obtained during ascent. This paper will focus on the low AoA ascent data. Since the high AoA during reentry makes interpretation of the SBLI experiment difficult, analysis of this portion of the flight is deferred.

III.   Instrumentation

The primary aerothermal instrumentation for HIFiRE-1 consisted of Medtherm Corporation coaxial thermocouples. Type E (chromel-constantan) thermocouples were installed in the SBLI region. Kulite® pressure transducers measured local static pressures. Figure 3 illustrates the transducer layout. All pressure transducers with the exception of those in the flare were model XCE-093. Those in the flare were XTEH-7LAC-190 (M). Each flare transducer output separate AC and DC-coupled signals that were digitized on different channels.

The coaxial thermocouples were dual-junction models that measured front-surface and back-surface (internal) temperatures simultaneously. These thermocouples were bonded into pre-drilled holes in the model surface using LOCTITE® adhesive. The thermocouples were installed with the backface junction flush to within 0.1 mm (estimated) of the model interior surface. The portion of the thermocouple which extended beyond the model external surface was removed using files and abrasives so that the final thermocouple contour matched the model surface contour.   This finishing process created a "sliver junction" between the center-wire and annular thermocouple materials, in which whiskers of one conductor are dragged over the other to create the thermocouple junction.
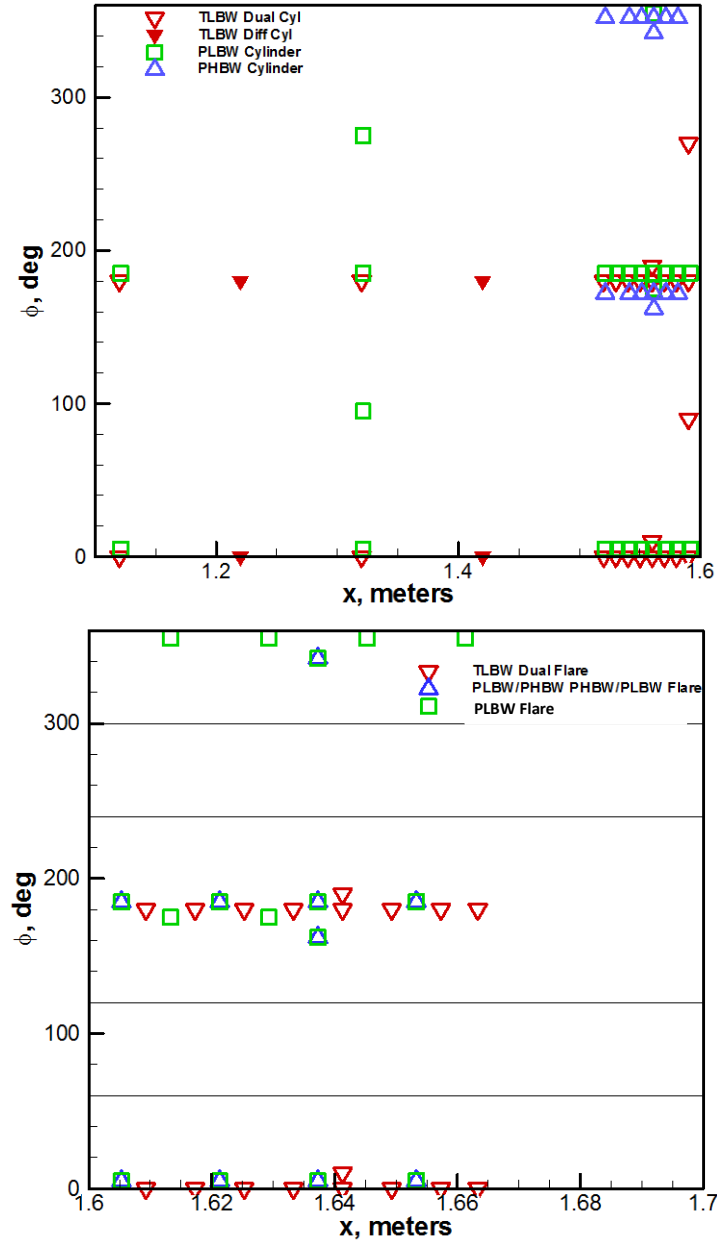
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Figure 3 SBLI Transducer Layouts

IV.   Computations

The computations proceeded in two stages. The first stage of computations consisted of calculations for test results from the CUBRC LENS wind tunnel. This permitted several transport models to be evaluated at wind tunnel conditions prior to employing them on the flight vehicle. Run 30 with M=7.19 and unit Reynolds Re=9.5x10^6/m, and α=0 was used as a test case. The model was full-scale, with a nose radius of 2.5 mm, identical to the flight configuration. The flare of the model was extended downstream to a larger diameter than the flight vehicle to ensure that attachment and equilibrium occurred on the flare. The focus of this effort was on the SBLI. In these calculations, turbulent transport was based on the SST turbulence model with and without a compressibility correction. Laminar flow assumed a constant Prandtl number Pr=0.7. Wall temperature in the computations was constant at T_w=300K. Transition was forced in the computations to match the wind tunnel transition location. Results shown in Figure 4 indicate that the Menter SST model, without compressibility correction, gave the best

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correlation with pressure and heat transfer measured in the SLBI. These results are in agreement with those of Maclean.[12] Also, computations with the SST model where boundary layer transition is near the nosetip, and ones where transition is forced in the computation near where it occurred in the test, show little effect of transition location on the SBLI pressures.
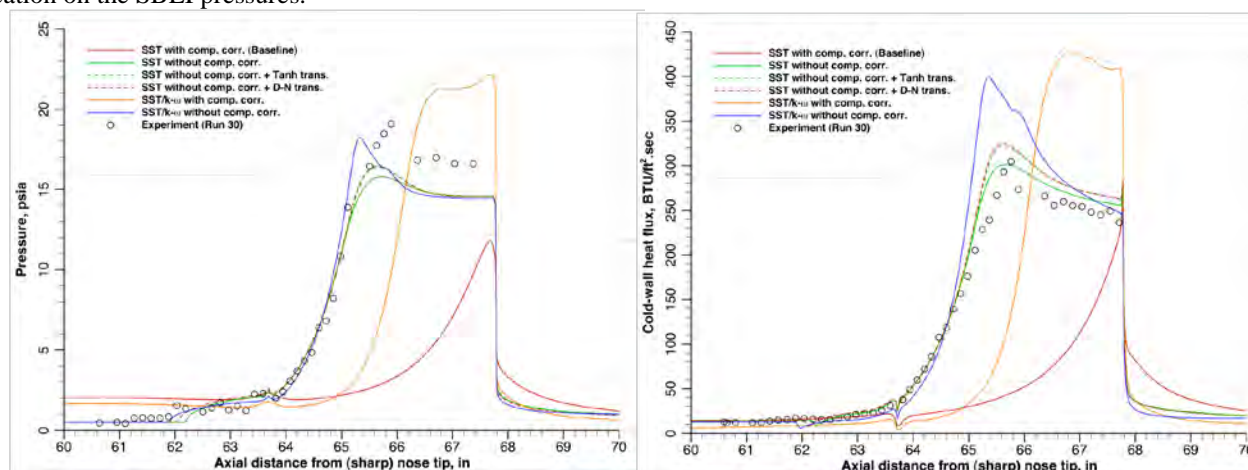

Figure 4 Computation of CUBRC run 30 with varying transport models and boundary conditions. Pressure left, heat transfer right.

In the second stage of computations, the entire flight vehicle was computed at a number of different times during the ascent. Two grids were used for these analyses. A 1633x537 grid was for $4.5 \leq t \leq 19.5$ s., and a 1632x367 grid was used for $20.5 \leq t \leq 23.5$ s. Calculations were carried out for wall temperatures of T_w= 300, 400 and 500K, approximately bounding the flight vehicle wall temperatures.

The effect of the boundary layer transition location on the SBLI was examined, but seemed to have little effect on computed results when transition was well upstream of the flare. Figure 5 shows measured and computed laminar and turbulent heat transfer on the cone at four times during ascent. These calculations were carried out for a wall temperature of 300 K. Since the flight wall temperature was higher than 300K, measured and calculated heating rates were converted to convective heat transfer coefficients based on wall and stagnation temperature. Error bars on the data are based on a +/-40 kW/m^2 uncertainty. For t=5.5 and 6 seconds, the measured heat transfer correlates well with predicted turbulent values. For t=15.5 and 21.5 seconds, the transition from laminar to turbulent heating on the cone is apparent.

Even though the cone contains a region of turbulent flow over its aft portion at t=21.5 seconds, measurements on the smooth-side SBLI begin to deviate from the tripped side slightly before this time. This departure is evident in Figure 6, which shows smooth and rough-side temperatures on the first transducer on the flare downstream of the corner. Temperatures on both sides of the payload agree well until t=20 seconds. At this point, temperatures on the smooth side begin to rise and spike at approximately t=22 seconds. After this, temperatures decay. It is surmised that this behavior was due to the transitional nature of the flow over the smooth side of the payload. Therefore, comparisons between measured and computed SBLI quantities will be constrained to times less than 20 seconds when transition occurs well upstream on the cone.

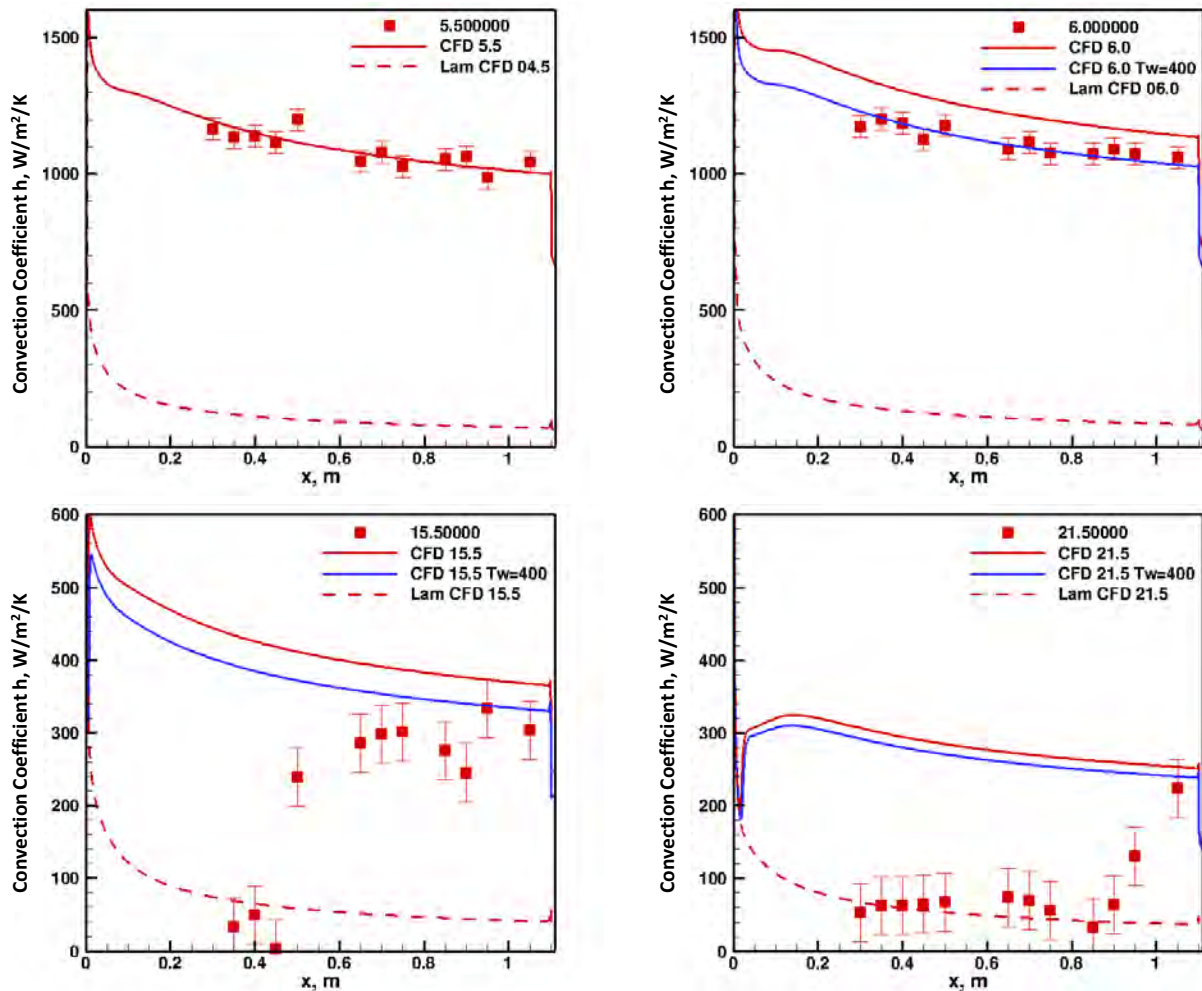American Institute of Aeronautics and Astronautics

Figure 5 Measured and computed cone heat transfer at various times.
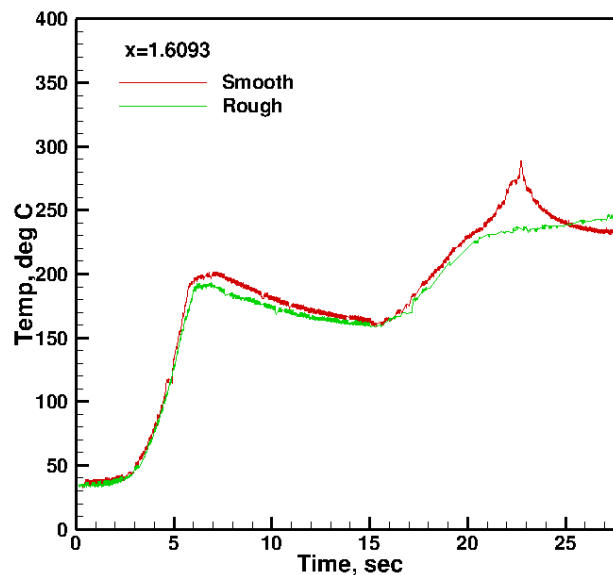
Figure 6 Measured smooth and rough-side temperatures on the flare during ascent.

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V. Pressure

Figure 7 summarizes measured and computed pressure distributions in the SLBI at a variety of times during ascent. Rough-side data is included where available. Rough-side data agree with smooth-side data, within experimental scatter. Generally, the computation captures the upstream influence well. With the exception of t=5.5 seconds, computations agreed with measured pressures on the cylinder and flare until the second-stage burn began at t=16 seconds. After this time, measured and computed pressures on the cylinder agree will, but measured pressures on the flare deviate from the computations. The amount of deviation increases with time.
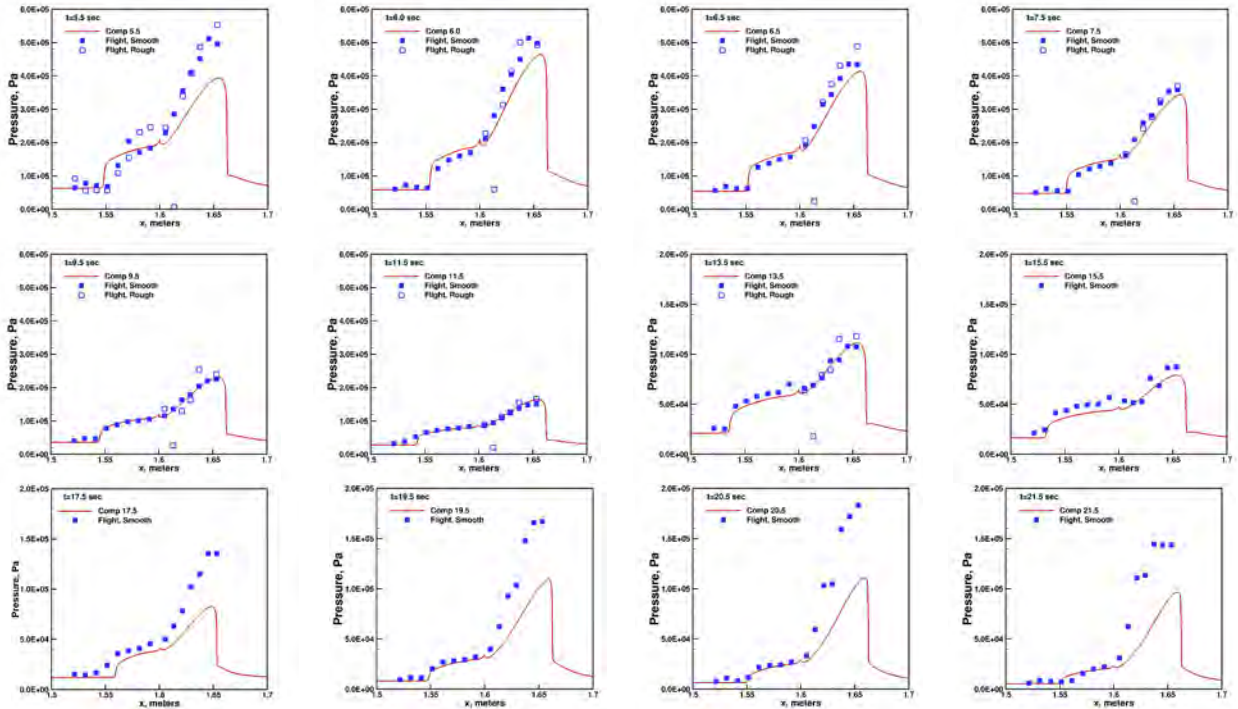

Figure 7 Measured and computed SBLI pressure distributions during ascent.

Several possible causes for the large flare pressure overshoots during second-stage burn were examined. The pressure transducers were temperature and acceleration-compensated, so the increased flare temperature or the acceleration during boost was unlikely to have produced the overshoot. Also, even though the Orion second-stage thrust dropped at about 19.3 seconds as the motor entered a sustain-burn phase, causing the payload axial acceleration to drop, the flare pressure overshoot remained high. The temperature boundary condition was examined as another possible cause. Figure 8 shows the effect of increasing the surface temperature from 300 K to 500 K in the computation. As expected, this has little effect on the surface pressures. Increased temperature causes a slight reduction in the computed surface pressure. The increased temperature causes a slight expansion of the upstream influence, probably due to the increase in boundary layer thickness attendant with the higher wall temperature.
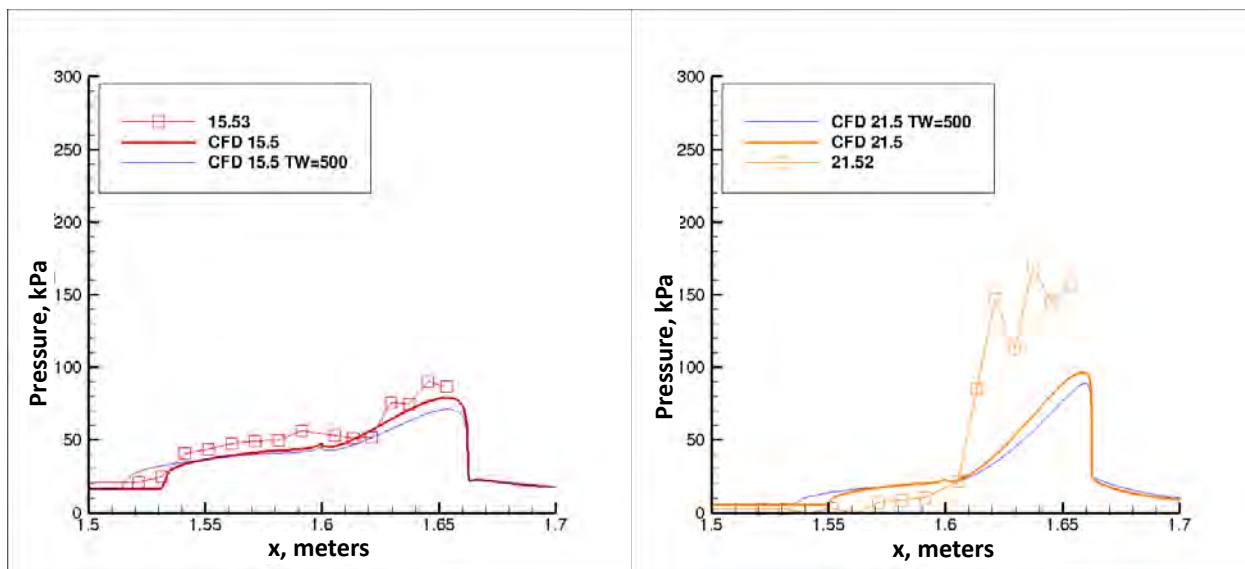
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Figure 8 Effect of surface temperature on SBLI pressure

In order to understand the high pressures seen on the flare, the measured and computed pressures were compared to expected inviscid flare pressures. The inviscid flare pressures were derived from the Taylor-Maccoll solution for a 33° half-angle cone. For the times examined, the computations show undershoots of the inviscid pressure. For $t \leq 17.5$ seconds, the experimental data show either an undershoot or a modest overshoot of inviscid pressure. At later times, the measured pressures overshoot the inviscid levels by large amounts. Although some pressure overshoot is expected at reattachment in a SBLI, the measured flight pressures far exceed any overshoot amounts observed in ground test. For this reason, measured pressures on the flare for times greater than 17.5 seconds must be viewed with skepticism. Although some transitional effects may come into play for $t \geq 20$ seconds, the mechanism behind these large overshoots remains unknown. Therefore, it can only be concluded that the large pressure overshoots on the flare were spurious and non-physical. Although the transducers were temperature and acceleration compensated, it may be possible that some factors caused this compensation to be ineffective. Another possibility, is that boost acceleration caused mechanical strain in the transducers, leading to erroneous results.
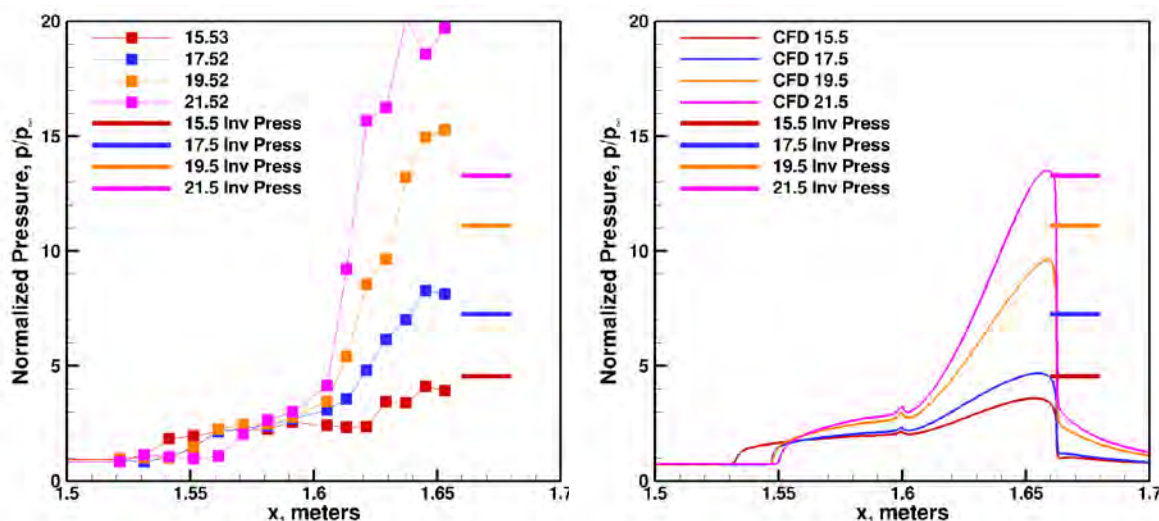

Figure 9 Measured and computed pressures compared to expected inviscid flare pressures.

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VI.   Heat Transfer

Figure 10 illustrates the comparison between measured and computed heat transfer in the SBLI after first-stage burnout. Since the CFD was computed at a constant wall temperature, and the experimental wall temperatures varied in space and time, the heating is compared on the basis of the convective heat transfer coefficient, h. The convective heat transfer coefficient h is evaluated based on the measured or computed temperature and the stagnation temperature, $h = \dot{q}/(T_0 - T_w)$. Although the heat transfer coefficient is better evaluated using the recovery temperature, this quantity is difficult to evaluate, and the impact on heat transfer coefficient is minimal unless the wall temperature approaches the recovery temperature.

The agreement between the measured and computed heat transfer is fair, and this is due mostly to the large scatter in the measured heat transfer. This is especially true for t=15 and 17.5 seconds, when the heating rates were very low.
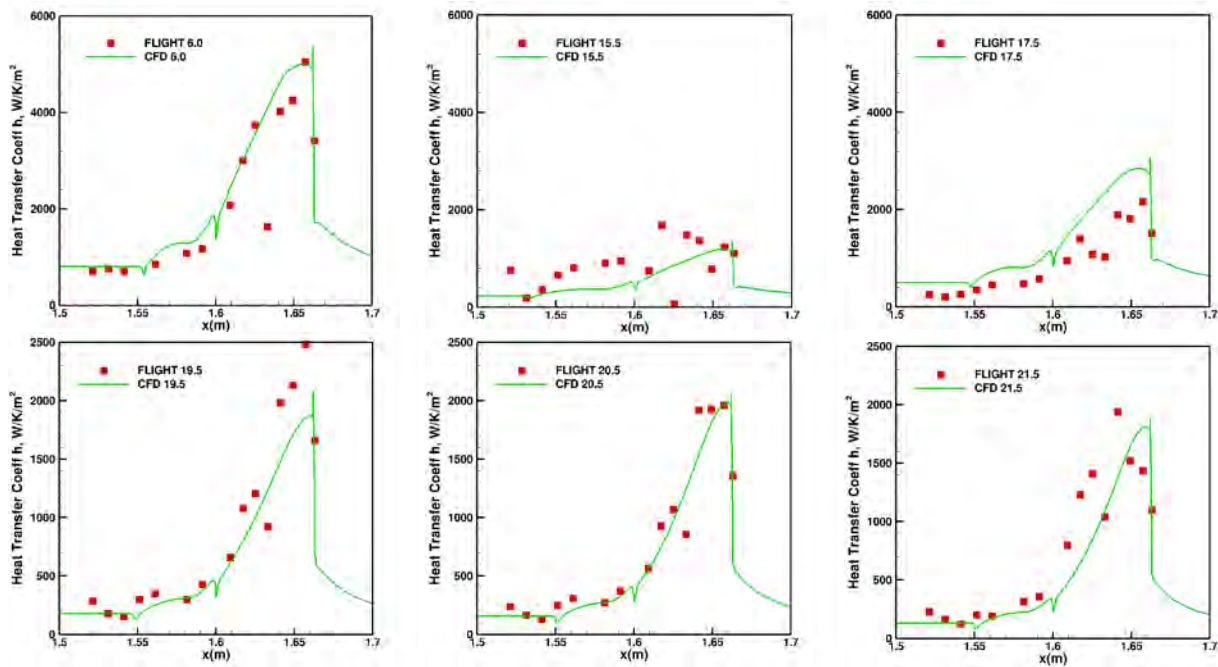

Figure 10 Measured and computed heat transfer.

VII.   Conclusions and Future Work

The DPLR code using the SST turbulence model with no compressibility correction performed well in predicting the SBLI pressure and heat transfer over most of the HIFiRE-1 ascent. This performance is in agreement with expectations based on experimental / computational comparisons with ground tests at CUBRC at Mach 7. Flight data during the second-stage boost showed significant pressure overshoots on the flare. The mechanism behind these overshoots, or whether they are even physical or due to sensor malfunction, is unknown. Overall, the good agreement between the measured flight data and the computations helps to validate the strategy of calibrating CFD against wind tunnel tests prior to exercising codes at flight conditions.

Acknowledgments

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